Fast adaptive multi-frequency all-optical scanning acoustic microscope

Steve D Sharples, Matt Clark, Nor Azhar Mohd Arif and Mike Somekh

Applied Optics, Electrical and Electronic Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, UK, email: steve.sharples@nottingham.ac.uk

Abstract—A noncontact and completely damage-free instrument capable of rapid high resolution vector contrast imaging using surface acoustic waves is described. The laser source of the ultrasound generates around 30 pulses at 82MHz and harmonics thereof, and it is possible to image at several discrete frequencies—82MHz, 164MHz, 246MHz and above—simultaneously. Adaption of the spatial distribution of the excitation source to accommodate a wide range of materials and circumstances is trivial, since a spatial light modulator is used to produce an arbitrary distribution of incident optical energy. This is used to good effect in anisotropic materials with random grain structures, since the material microstructure perturbs the surface waves as they propagate on the material surface. The wavefront aberrations are detected by an acoustic wavefront sensor, and the excitation profile is adjusted to correct for the aberrations. This increases the accuracy and reliability of the measurements, and can increase the usable frequency range or propagation distance for a given material.

The adaptable source enables the instrument to be used for purposes other than linear surface wave detection and c-scan imaging; for instance, the SAW phase velocity of anisotropic crystals may be determined by wavenumber spectroscopy achieved by adapting the source k-vector and finding the peak in excitation. Also, there is considerable interest in nonlinear and harmonic detection and imaging, and the adaptable source may be used to suppress the harmonics naturally present in the excitation source. This is important for harmonic imaging, where it is necessary to ensure that the relatively weak harmonics generated by the nonlinear material properties are not swamped by those present in the source.

I. Introduction

Laser ultrasound has been a promising technique for acoustic imaging for some time. In particular the lack of a liquid couplant—generally required for contact techniques such as the scanning acoustic microscope—is a great strength of completely noncontact techniques in general. The couplant can be problematic in several ways: contamination of the sample, perturbation of the acoustic waves, damping can eliminate certain contrast mechanisms, and the nonlinearity of the coupling mechanism dominates any material nonlinearity, preventing direct measurement of high order elastic constants.

Although optical generation and detection of ultrasound has been commonplace for many years, there are still several inherent disadvantages of the technique compared to the use of contact transducers. A common problem is the lack of detector sensitivity, which is typically one or two orders of magnitude less [1]. Although it is possible to apply more and more optical power to generate ultrasound of greater amplitude, this tends to result in the sample being damaged. Whilst this may not be a problem on some materials, in many circumstances this would be considered unacceptable.

In addition, the signal-to-noise ratio (SNR) of an all-optical system operating in the thermoelastic regime is proportional to $P_{gen}\sqrt{P_{det}}$, where P_{gen} is the optical power used to generate the surface wave, and P_{det} is the optical power used to detect it [1], [2]. This implies that there is much more to gain from increasing the generation power than from increasing the detection power. The signal to noise ratio is particularly relevant if you wish to perform imaging with an all-optical system, where high speed data acquisition is required.

The optical scanning acoustic microscope (O-SAM) instrument precisely controls the optical distribution of the ultrasound source. This is done so that as much of the available optical power is used efficiently and effectively to obtain surface acoustic waves of sufficiently large amplitudes for optical detection, but without causing any damage to the sample under investigation. There are two mechanisms by which this is achieved, illustrated in figure 1: by *focusing* the ultrasound to a finite region, producing amplitude gain at the focus; and by *distributing the power* of the incident laser energy. These two complementary techniques are combined to greatly enhance the maximum available surface acoustic wave amplitude, which is very important if a practical all-optical imaging system is to be realized. It has increased the SNR in our system by a factor of around 80, compared to a single line source just below the threshold limit [3], equivalent to increasing the optical detection power by around 5000.

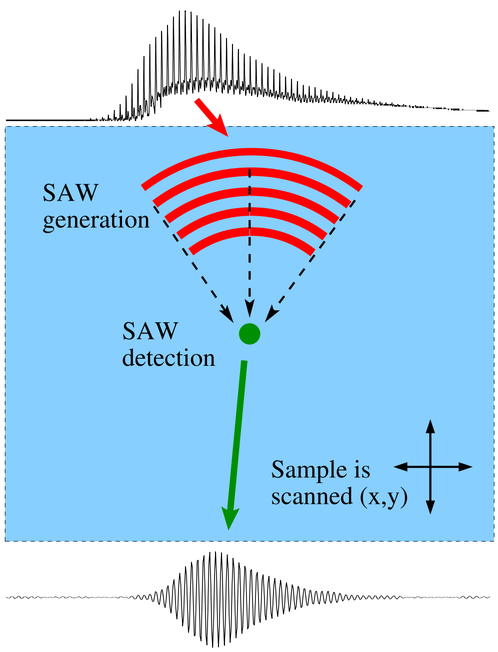

Figure 1. Illustration of the optical excitation profile used to generate focused surface acoustic waves. The SAWs are detected at the acoustic focus using an optical probe. The sample is scanned whilst the separation between excitation and detection regions remains constant.

This precise control of the optical distribution allows for precise control of the resulting ultrasound propagation in terms of modes, frequency content and spatial distribution. This may be used to attain other goals, other than the maximum possible SAW amplitude available.

II. Instrumentation

Figure 1 illustrates the general concepts of the O-SAM instrument, whilst figure 2 provides a detailed illustration of the optical configuration used.

The laser used to generate the ultrasound is a Q-switched, mode locked Nd-YAG laser with a wavelength of 1064nm. In this mode of operation, the mean output power of the laser is around 2W, and the peak energy from a pulse is of the order of 0.3mJ. An envelope of approximately 30 sharp pulses with a separation of 12.1ns (corresponding to a fundamental frequency of 82MHz) is emitted from the laser every 0.2–1ms—this is illustrated in the upper part of figure 1. The energy from the pulsed generation laser is applied to the surface of the sample via optics that both focus the light onto the sample and control its spatial distribution. The sample is mounted on automated mechanical stages to enable the formation of c-scan images. The surface acoustic waves propagate on the sample surface, and are then detected at the acoustic focus by focusing a continuous wave laser onto the sample surface and measuring the angular deflection. Analogue amplitude and phase detection electronics then amplify and convert the signals from the detector into a form suitable for acquisition by a host computer.

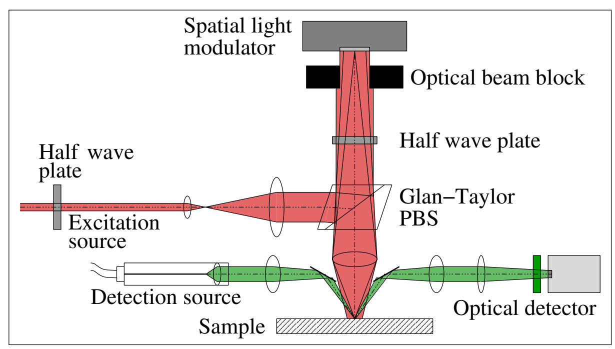

Figure 2. Optical configuration of the O-SAM instrument.

Figure 2 illustrates the optical configuration of the O-SAM instrument. The spatial distribution of the optical energy on the surface of the material used to excite the SAWs is controlled by a spatial light modulator (SLM). This 512 × 512 pixel device, manufactured by Boulder Nonlinear Systems, works by rotating the polarization of the reflected light by up to ±45°. This change of phase is converted to a change in optical intensity (for each pixel) by a Glan-Taylor polarizing beam splitter. Thus an intensity pattern, corresponding to the image applied to the SLM, is imaged onto the surface of the sample to form the SAW excitation pattern.

The optical detector used to detect the SAWs is a

16-channel acoustic wavefront sensor (AWFS), developed specifically for the O-SAM instrument, and is a linear array of 16 split photodiodes, constructed using a standard 0.7μm CMOS process. This process is used so that in future iterations of the AWFS design, the data acquisition electronics can be integrated with the optical sensor.

A green laser is focused onto the sample at the acoustic focus using a standard lens. A slight astigmatism is added by the addition of a weak cylindrical lens, to produce a line approximately 400μm long on the sample surface that is diffraction limited in the orthogonal direction—the direction of SAW propagation. This line is then imaged onto the AWFS using another set of lenses. As different parts of the line on the sample are perturbed by the acoustic wavefront, the perturbations are detected by elements of the 16 channel array according to their position. The importance of capturing the acoustic wavefront (rather than a single point) will be illustrated in the section where we deal with the effects of acoustic aberration.

Because the tailored excitation profile produces SAW waves of sufficient amplitude to be detected without the need of coherent digital averaging, an extremely rapid analogue detection technique may be employed to acquire the amplitude and phase data from the instrument. This technique allows us to capture the complex amplitude of the detected acoustic wave, at each of the 16 points of the wavefront sensor, for each of the acoustic frequencies we wish to image (82MHz, 164MHz, 246MHz etc). The technique used is to mix the received acoustic signal with a coherent reference signal of the same frequency—acquired from the generating laser mode locker driver—in quadrature. The advantages over digital techniques—namely speed, cost, simplicity and upper frequency limit—are significant, especially when multiple detection points at multiple frequencies are to be acquired at speeds suitable for imaging.

III. Adaption

The flexible SAW excitation profile affords us great control of the generated acoustic waves, in terms of the frequencies of SAWs generated, and their spatial distributions. Some examples of why this is an extremely useful feature are described and illustrated in this section.

Rapid SAW velocity measurement on anisotropic crystals

The amplitude of the excited acoustic waves depends on the spacing of the lines of optical energy imaged onto the sample. If the lines are spaced such that they are one acoustic wavelength apart (at a given SAW frequency), then strong excitation will occur. Thus by finding the wavelength at which a peak excitation occurs (by adjusting the line spacing of the SLM image) the SAW phase velocity may be determined for a material. This may be done without mechanical movement of the detection probe, and is thus very rapid.

Adapting to the effects of material microstructure

A wave propagating through any aberrating medium is affected in some way by the medium; for example the light from a distant star is aberrated by the effects of the changing currents in the Earth's atmosphere. Acoustic waves propagating through an anisotropic medium—such as a polycrystalline metal—will also be aberrated because their velocity is determined by the [random] grain orientations. As different parts of the acoustic wavefront propagate through different grains, the wavefront tends to either end up in a different location to that expected, or to break up completely. This, in turn, can lead to severe degradation in the quality of the c-scan images obtained at even modestly high frequencies [4].

The O-SAM is an excellent instrument with which to observe this effect, since the amplitude and phase of the surface waves can be imaged as they propagate from the excitation region to the point where the detector would normally be. Figure 3a illustrates how wavefront aberration affects focused surface acoustic waves.

Figure 3 shows aerial and line point spread functions (PSFs) of the amplitude of 82MHz Rayleigh waves, as they propagate from the top of the figure downward. The intention is to focus the waves to a diffraction-limited region, to increase their amplitude and to localize their interaction to a certain place on the sample, namely the center of the aerial PSF. This is clearly not occurring in figure 3a; the PSF has broadened and dispersed, and the peak amplitude along the PSF is low and no longer at the intended location. The AWFS can acquire a 16 point PSF along the line of the intended focus. We back-propagate the measured wavefront to the excitation region using an angular spectrum propagation technique [5], where the phase error is calculated compared to the geometric generation profile. The error is then used to generate a new excitation profile using the SLM, to correct for the material aberrations. This is achieved in figure 3b, where the PSF is much more clearly defined, with a higher peak amplitude at the center.

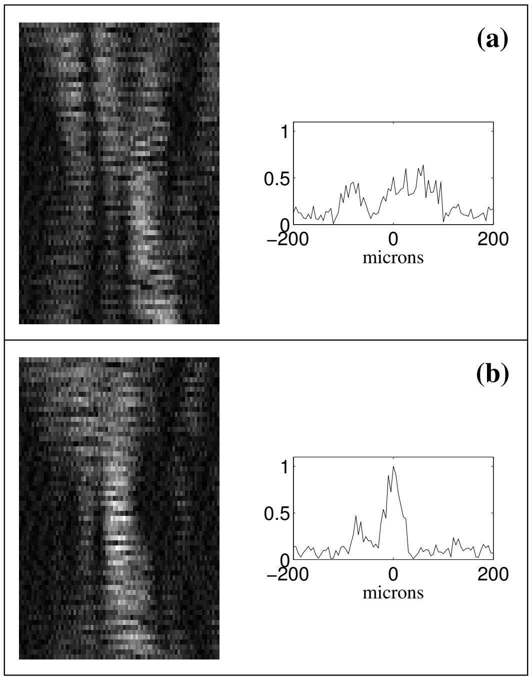

Figure 3. Aerial (left) and line (right) point spread functions of the amplitude of 82MHz SAWs as they propagate on an aberrating material. The measured wavefront in a is used to calculate a new excitation profile, to greatly improve the point spread function characteristics (b).

Advanced multi-frequency control of the acoustic field

There is considerable interest in performing nonlinear and harmonic imaging in the field of nondestructive evaluation, since the nonlinear acoustic response is more sensitive to damage than the linear response. Typically, acoustic waves may be excited at a frequency f, and a small amount of acoustic waves at the harmonic $2f$ may then be detected due to the nonlinear response of the material. For the measurement to be successful, it is of paramount importance to ensure that the harmonic signal detected can legitimately be attributed to the nonlinear behavior of the material, rather than harmonic contamination of the excited acoustic wave due to nonlinearities in the excitation process.

Figure 4 illustrates one of the ways this may be achieved, which is by spatial separation of the fundamental and the harmonic. The figure shows PSFs at 82MHz and 164MHz acquired simultaneously. By careful adaption of the excitation profile, the acoustic fields of different frequencies can be manipulated in different ways.

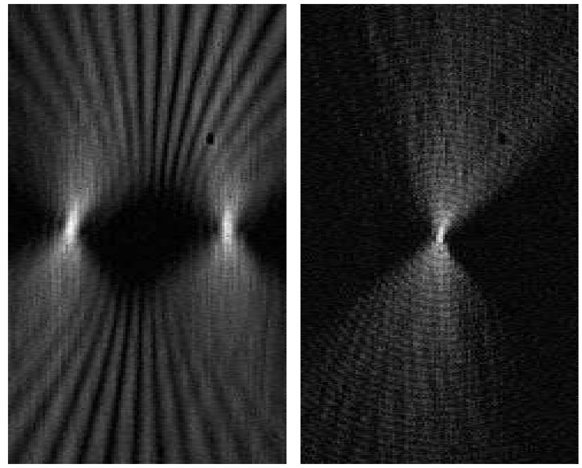

Figure 4. 82MHz (left) and 164MHz (right) SAW PSFs, acquired simultaneously from the same excitation profile. The focuses of the fundamental frequency and the harmonic are spatially separate.

IV. Conclusions

This paper has illustrated the flexibility and power of the O-SAM instrument. Its ability to adapt in a number of ways to the nature of the material and the desired type of measurement has been shown. The ability to correct for material aberrations will extend the range of materials that can be imaged at high frequencies, and the ability to control the spatial distributions of acoustic waves of different frequencies offers exciting potential in the area of nonlinear imaging for nondestructive evaluation.

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